

# North-south asymmetry in small and large sunspot group activity and violation of even-odd solar cycle rule

J. Javaraiah<sup>1</sup>

**Abstract** According to Gnevyshev-Ohl (G-O) rule an odd-numbered cycle is stronger than its preceding even-numbered cycle. In the modern time the cycle pair (22, 23) violated this rule. By using the combined Greenwich Photoheliographic Results (GPR) and Solar Optical Observing Network (SOON) sunspot group data during the period 1874–2015, and Debrecen Photoheliographic Data (DPD) of sunspot groups during the period 1974–2015, here we have found that the solar cycle pair (22, 23) violated the G-O rule because, besides during cycle 23 a large deficiency of small sunspot groups in both the northern and the southern hemispheres, during cycle 22 a large abundance of small sunspot groups in the southern hemisphere. In the case of large and small sunspot groups the cycle pair (22, 23) violated the G-O rule in the northern and southern hemispheres, respectively, suggesting the north-south asymmetry in solar activity has a significant contribution in the violation of G-O rule. The amplitude of solar cycle 24 is smaller than that of solar cycle 23. However, Coronal Mass Ejections (CMEs) rate in the rising phases of the cycles 23 and 24 are almost same (even slightly large in cycle 24). From both the SOON and the DPD sunspot group data here we have also found that on the average the ratio of the number (counts) of large sunspot groups to the number of small sunspot groups is larger in the rising phase of cycle 24 than that in the corresponding phase of cycle 23. We suggest this could be a potential reason for the aforesaid discrepancy in the CME rates during the rising phases of cycles 23 and 24. These results have significant implication on solar cycle mechanism.

**Keywords** Sun: Dynamo – Sun: surface magnetism – Sun: activity – Sun: sunspots

## 1 Introduction

A number of authors have shown the existence of a difference in the number as well as the dynamic behaviors of sunspots in the northern and the southern hemispheres. In fact, the existence of north-south asymmetry in solar activity is well established (Roy 1977; Hathaway 2015, and references therein) and the existence of several short- and long-term periodicities in the north-south asymmetry is also known (Swinson *et al.* 1986; Carbonell *et al.* 1993; Verma 1993; Duchlev and Dermendjiev 1996; Javaraiah and Gokhale 1997a; Li *et al.* 2002; Knaack *et al.* 2004; Chang 2009; Chowdhury *et al.* 2013; Ravindra and Javaraiah 2015). Phase relationship of activity in northern and southern hemispheres and its implication on Gnevyshev gaps, etc. were also investigated (Temmer *et al.* 2006; Zolotova and Ponyavin 2006; Donner and Theil 2007; Norton and Gallagher 2010). North-south asymmetry in the solar activity during a solar cycle can be used to predict amplitude of next cycle (Javaraiah 2007, 2008, 2015). Solar activity influences on the space weather and also may have an influence on the terrestrial climate (Shapira *et al.* 2011; Clette *et al.* 2014; Hathaway 2015; Gopalsawmy *et al.* 2015a). North-south asymmetry of solar activity seems to have a role on the atmospheric circulations (Georgieva *et al.* 2007).

One of the well known properties of solar cycles is the existence of Gnevyshev-Ohl rule or G-O rule (Gnevyshev and Ohl 1948). According to this rule an odd numbered cycle is stronger than the preceding even numbered cycle. However, some pairs of even and odd numbered solar cycles violated this even-odd cycle rule. It seems the violation of this rule is followed

J. Javaraiah

<sup>1</sup> #58, BSK 5th Stage, Bikasipura (BDA Layout), Bengaluru-560 111, India

Formerly with Indian Institute of Astrophysics, Bengaluru-560 034, India

by a few weak cycles. The cycle pair (22, 23) violated the even-odd cycle rule. The current activity level is much lower in the last 100 years also. The activity trend over last 20 years may resemble the Dalton minimum (Zolotova and Ponyavin 2014; Javaraiah 2015). Tlatov (2015) found that the secular minima of the solar activity occurs in the vicinity of the extreme points of the 200-year cycle of inversion of G-O rule.

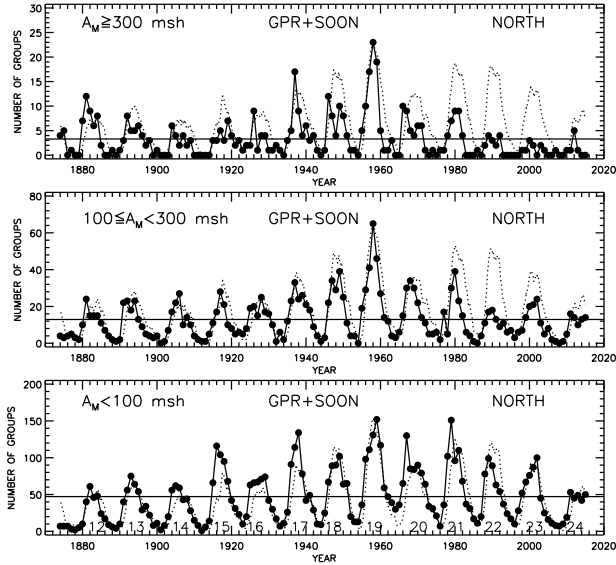
The dynamic behaviors of the magnetic structures of large and small sunspot groups are different (Ward 1965, 1966), may be due to differences in dynamics of solar plasma at different subsurface layers of the Sun (*e.g.* Howard 1996; Javaraiah and Gokhale 1997b; Hiremath 2002; Sivaraman *et al.* 2003; Javaraiah 2013). Recently it has been shown that different classes of sunspot groups behave differently over a cycle (Kilcik *et al.* 2011; Lefèvre and Clette 2011; Clette and Lefèvre 2012; Javaraiah 2012a; Obridiko and Badalyan 2014). In the earlier analysis (Javaraiah 2012a) it was found that the cycle pair (22, 23) violated G-O rule in  $R_Z$  due to a large deficiency of the small sunspot groups in cycle 23. In this paper we have investigated the north-south differences in the numbers of large and small sunspot groups and their implication on the G-O rule. Such a study is important for understanding the north-south asymmetry of solar activity relationship with the Sun's subsurface dynamics and solar cycle.

The solar flares and CMEs originate from solar active regions. Thus, the frequencies of occurrence of CMEs well correlated to the international sunspot number ( $R_Z$ ). The X-class flares occur in any phase of solar cycles (Hathaway 2015). It is known that the CME productivity increases with active region size (Canfield *et al.* 1999; Ramesh 2010). Recently, Gopalsawmy *et al.* (2015a) and Gopalswamy *et al.* (2015b) have found that though the peak of the current sunspot cycle 24 is smaller than that of sunspot cycle 23, in the rising phase of cycle 24 halo CMEs abundance is relatively large. This discrepancy in the behavior of CME rates and sunspot activity in the rising phases of cycles 23 and 24 is not yet understood (Gopalswamy *et al.* 2015b). In view of the aforesaid discrepancy in CME rates during the rising phases of the cycles 23 and 24, here we have also investigated on the ratio of the number of large sunspot groups to the number of small sunspot groups during the rising phases of cycles 23 and 24, because it may be providing an important clue for understanding the aforesaid discrepancy in the CME rates.

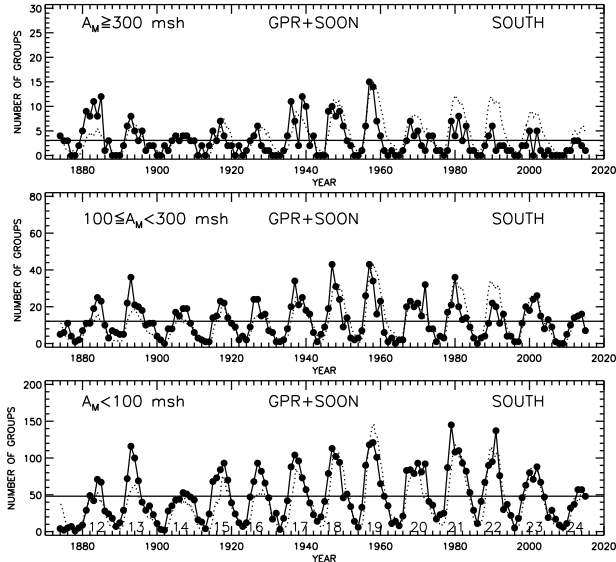
In the next section we described the data analysis, in Section 3 we described the results, and in Section 4 we summarized the results and their implications.

## 2 Data analysis

Here we have used the combined Greenwich and SOON sunspot group data during the period 1874–2015 (available at <http://solarcience.msfc.nasa.gov/greenwich.shtml>). David Hathaway scrutinized the GPR and SOON sunspot group data and produced a reliable continuous data series from 1874 up to date (Hathaway *et al.* 2003; Hathaway and Choudhary 2008; Hathaway 2015). The Royal Greenwich Observatory terminated the publication of GPR at the end of 1976. Since 1977 Debrecen Heliophysical Observatory took over this task (for detail see Györi *et al.* 2010). The DPD sunspot group data during 1974–2015 are available at <http://fenyi.solarobs.unideb.hu/pub/DPD/>. We also analyzed this data and compared the results found from this and SOON data sets. The data reduction and analysis are same as in Javaraiah (2012a). The data consist the values of the date and the time of observation, heliographic latitude and longitude, corrected whole spot area ( $A$ ), etc., of each of the sunspot groups observed in each day during their respective life times of the sunspot groups. In case of SOON data, we increased area by a factor of 1.4. This is necessary to have a uniform combined GPR and SOON data (Hathaway and Choudhary 2008; Hathaway 2015). The maximum area of a sunspot group having life time  $n$  days is defined as  $A_M = \max(A_1, A_2, \dots, A_n)$ , where  $A_1, A_2, \dots, A_n$  are area measured in  $1^{st}, 2^{nd}, \dots, n^{th}$  days. We have used here only the sunspot groups having life time at least  $n = 2$  days. In the aforementioned paper relatively long-term variations in the yearly numbers (counts) of the small (maximum area  $A_M < 100$  millionth of solar hemisphere, msh), large ( $100 \leq A_M < 300$  msh), and very-large ( $A_M \geq 300$  msh) sunspot groups are studied by analyzing the combined data of all the sunspot groups occurred in the Sun's whole sphere (Note: here we have replaced the word 'big', which was used in our earlier papers, with words 'very-large'. This is because we find that the words 'large' and 'big' give same/equivalent meaning. Hence, it causes some confusion to the readers on the classifications of the sunspot groups). The north-south difference/asymmetry in the solar cycle variations in the yearly numbers of the small, the large, and the very-large sunspot groups are studied. The ratio of the number of large to the number of small sunspot groups during the ascending phases of solar cycles 23 and 24 are also determined (note: for the sake of better statistics, in this case the large and the very large sunspot groups have been combined.)



**Fig. 1** Plots of the values of the numbers of small (lower panel), large (middle panel), and very-large (upper panel) sunspot groups in the northern hemisphere versus time (year) during the period 1874–2015. The horizontal lines represent the corresponding mean values. The dotted curve represents variations in the normalized 13-month smoothed  $R_Z$ . In the lower panel near maximum epoch of each solar cycle the corresponding Waldmeier cycle Number is given.

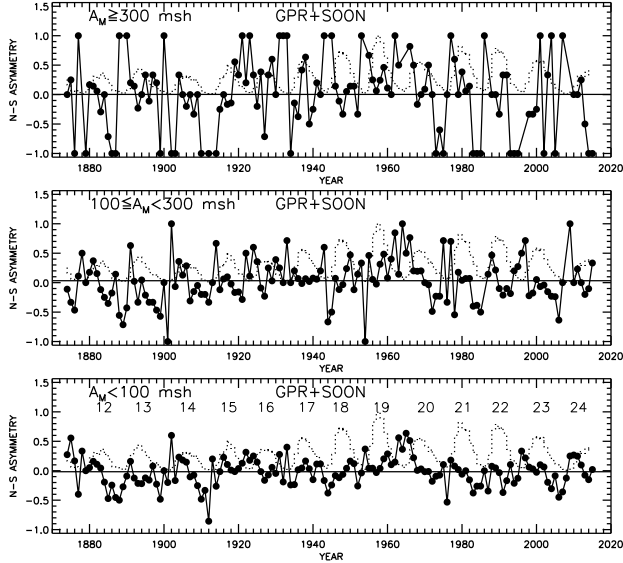


**Fig. 2** The same as Fig. 1 but determined from the data of the sunspot groups in the southern hemisphere.

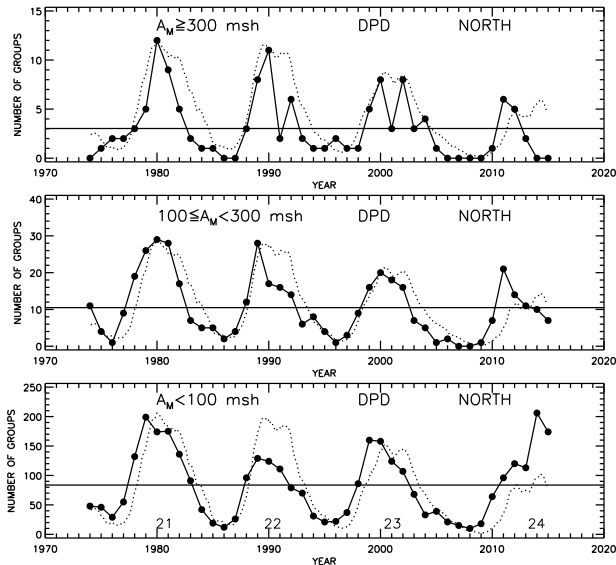
### 3 Results

Figs. 1 and 2 show variations in the yearly numbers of small, large, and very-large sunspot groups in the northern and the southern hemispheres, respectively, during the period 1874–2015. For the sake of checking the solar cycle properties in these variations, in Figs. 1 and 2 we have also showed the variation in the 13-month smoothed international sunspot number  $R_Z$ , taken from <http://www.ngdc.noaa.gov/> (Note: for the sake of scaling  $R_Z$  is normalized). As can be seen in these figures there exist 11-year solar cycle patterns in the variations of all the three classes of sunspot groups in each hemisphere. Overall the variations in the numbers of small, large, and very-large sunspot groups in each hemisphere are largely same as the corresponding variations determined by Javaraiah (2012a) from the whole sphere data. However, the existence of north-south differences in these variations are noticeable during some cycles.

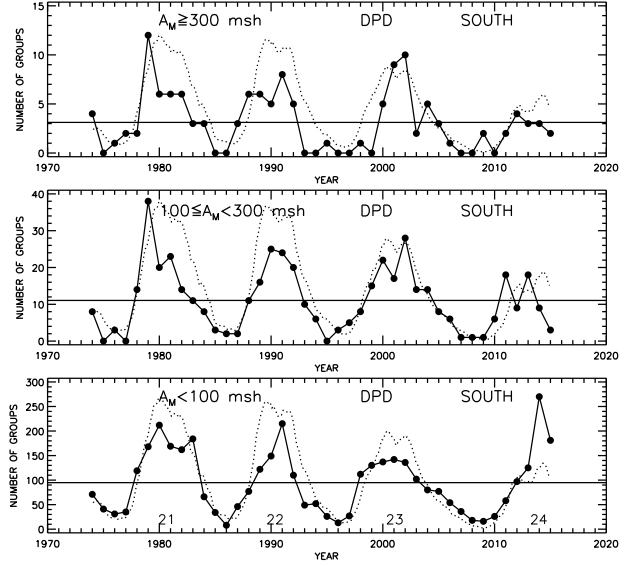
In many studies the north-south asymmetry in solar activity is determined as  $(N - S)/(N + S)$ , where  $N$  and  $S$  are the amounts of activity in the Sun's northern and southern hemispheres, respectively (Newton and Milsom 1955; Swinson *et al.* 1986; Carbonell *et al.* 1993; Verma 1993; Duchlev and Dermendjiev 1996; Javaraiah and Gokhale 1997a; Knaack *et al.* 2004). Because of relatively less error in this ratio (Javaraiah and Gokhale 1997a), it may be worth to check the variation in this ratio rather than in the absolute north-south difference. Fig. 3 shows the variations in the corresponding north-south asymmetry of the yearly counts of small, large, and very-large sunspot groups. In this figure we have also showed the variation in the 13-month smoothed  $R_Z$ . In this figure the extreme values  $-1$  and  $+1$  of the north-south asymmetry in the number of a class of sunspot groups imply the absence of the corresponding class of sunspot groups in the northern and the southern hemispheres, respectively. Such epochs are more in the case of the number of very-large sunspot groups, causing large inconsistency in the corresponding time series. In some years the values are equal to zero because the numbers of corresponding sunspot groups are equal in northern and southern hemispheres. There are some gaps in the time series (see closed circle curve) due to absence of the data in both the hemispheres. Such gaps are also more in the case of the number of very-large sunspot groups. As can be seen in this figure, the north-south asymmetry patterns in the numbers of all the three classes of sunspot groups are similar. There is also an indication that the north-south asymmetry is multiperiodic in nature. In the declining phases closer to the minima of a large number of solar cycles the values of the north-south asymmetry are relatively high



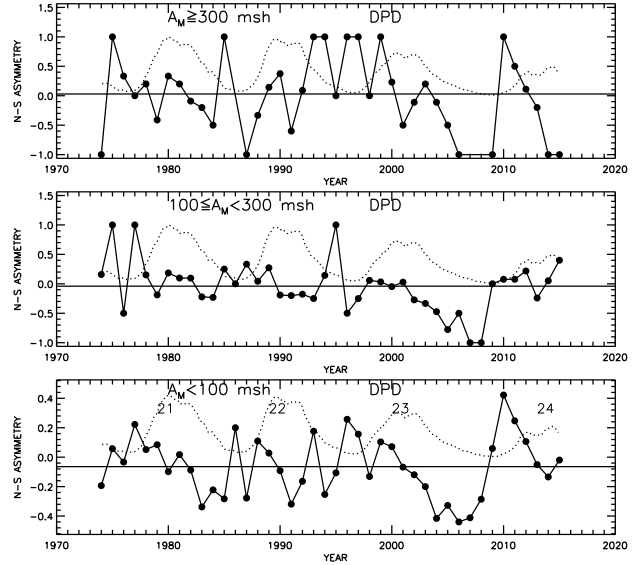
**Fig. 3** Plots of the values of the north-south asymmetries in the numbers of small (lower panel), large (middle panel), and very-large (upper panel) sunspot groups versus time (year) during the period 1874–2014. The horizontal lines represent the corresponding mean values. The dotted curve represents variations in the normalized 13-month smoothed  $R_Z$ . In the lower panel near maximum epoch of each solar cycle the corresponding Wald-meier cycle Number is given.



**Fig. 4** The same as Fig. 1 but determined from the DPD data of the sunspot groups during 1974–1915.



**Fig. 5** The same as Fig. 2 but determined from the DPD data of the sunspot groups during 1974–1915.



**Fig. 6** The same as Fig. 3 but determined from the DPD data of the sunspot groups during 1974–1915.

in each class of sunspot groups. There are some trends in the north-south asymmetry of the number of large sunspot groups (and even in the asymmetry of the number of very-large sunspot groups) which suggest the following: before cycle 16 during the minima of a large number of cycles large sunspot groups were more in the southern hemisphere, during a large number of cycles between cycles 16 and 20 large sunspot groups were more in the northern hemisphere, and after cycle 20 during minima of the remaining cycles there seems to be the large sunspot groups were somewhat more in the southern hemispheres. At maximum epoch of cycle 23 the north-south asymmetry is very small in the number of small sunspot groups, whereas the asymmetry in the number of small sunspot groups is reasonably large at the maximum epoch of cycle 22 due to a large number of small sunspot groups in the southern hemisphere. In the declining phase of the strongest cycle 19, the asymmetry in each of the three classes of sunspot groups has positive values suggesting sunspot activity is large in the northern hemisphere. The trends indicate the existence of 11–12 year periodicity in the north-south asymmetry in the numbers of both the large and the small sunspot groups. In fact, the existence of this periodicity in the north-south asymmetry of solar activity is known (Carbonell *et al.* 1993; Javaraiah and Gokhale 1997a). The patterns of the north-south asymmetry in the number of small sunspot groups (and some extent the pattern in the number of large sunspot groups) during cycles 12–14 and cycles 21–23 are similar and they are differing with the pattern during cycles 16–20. That is, on the average over cycles 12–14 and also over cycle 21–23 the asymmetry seems to be negative (southern hemisphere dominance) and a large contributions to this property have come from the declining phases of these cycles. This long-term pattern suggests the existence of 55–65 year periodicity in the north-south asymmetry of the number of small sunspot groups.

As can be seen in Fig. 1 in the case of the number of small sunspot groups in the northern hemisphere cycle 18 is much weaker than cycles 17, and the cycles 22 and 23 are approximately equal in strength. As can be seen in Fig. 2 in the southern hemisphere cycle 18 is slightly stronger than cycle 17, and in fact, the strengths of the cycles 18 and 19 are approximately equal. As can be seen in Figs. 1 and 2 in the case of small sunspot groups in the northern hemisphere the even-odd cycle rule is not well defined during cycle 22 and cycle 23, whereas in the southern hemisphere it is very clear cycle pair (22, 23) violated the even-odd cycle rule (the difference between the corresponding amplitude of cycles 22 and 23 is significant on 95% confidence

level). In the case of large sunspot groups throughout cycles 12–23 the validity of even-odd cycle rule is unambiguous. That is, this rule seems to be valid even in the case of cycle pair (22, 23) in both the northern and the southern hemispheres, in consistent with the similar result found from the whole sphere data (Javaraiah 2012a). In the earlier analysis (Javaraiah 2012a) it was found that the cycle pair (22, 23) violated G-O rule in  $R_z$  due to a large deficiency of the small sunspot groups in cycle 23. Further here we find that the violation is caused mainly due to, besides in cycle 23 a large deficiency of small sunspot groups in both the northern and southern hemispheres, a large abundance of small sunspot groups during cycle 22 in the southern hemisphere. This is consistent with the pattern of north-south asymmetry in the number of small sunspot groups of cycles 22 and 23 as found above.

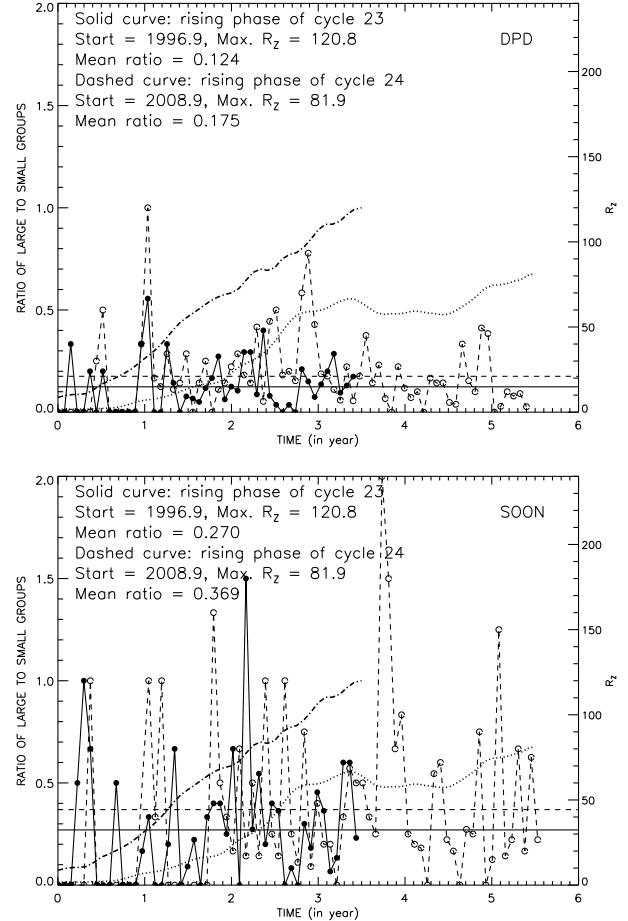
Figs. 4 and 5 show the variations in the numbers of small, large, and very-large sunspot groups in the northern and southern hemispheres, respectively, determined from the DPD sunspot group data during the period 1974–2015. Fig. 6 shows the variations in the corresponding north-south asymmetry in each of the three classes of sunspot groups. There is a large agreement between the variations in the number of each class of sunspot groups shown in these figures with the corresponding variations during cycles 21–24 shown in Figs. 1, 2, and 3. Overall the results found above from the SOON sunspot group data during cycle 21–24 are consistent with the variations shown in Figs. 4, 5, and 6. As can be seen in Figs. 4 and 5 in the case of small sunspot groups the violation of G-O rule by cycle pair (22, 23) is only in the southern hemisphere, whereas in the case of large sunspot groups it was happened only in northern hemisphere. Overall it seems north-south asymmetry has a significant contribution in the violation of G-O rule. During the Maunder minimum the activity (small sunspot groups in low latitudes) was present mainly in the southern hemisphere (Sokoloff and Nesme-Ribes 1994). As can be seen Fig.6 during the prolonged deep minimum between cycles 23 and 24 the north-south asymmetry in the number of small sunspot groups also indicates the southern hemisphere dominate with more small sunspot groups.

Kilcik *et al.* (2011) have found that in general large sunspot groups peaked about two years later than the small ones. We found that in many cycles the positions of the peaks of the small, large, and very-large sunspot groups are different, and they also deviate considerably from the corresponding peak positions of  $R_z$  (Javaraiah 2012a). The current sunspot cycle 24 has double peaks or Gnevyshev peaks (Gnevyshev 1963,

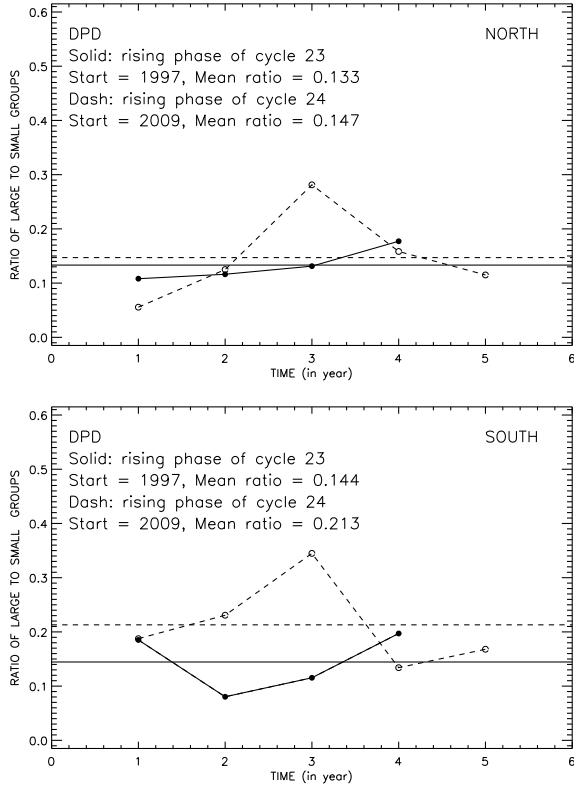
1967). Norton and Gallagher (2010) found that the Gnevyshev Gap (*viz.*, the gap between the Gnevyshev peaks) is a phenomena that occurs in both hemispheres and is not due to the superposition of two hemispheres out of phase with each other. Kilcik and Ozguc (2014) suggested that one possible reason for a double-peaked maximum in a solar cycle is the different behavior of large and small sunspot groups, resulting from the existence of two different dynamo mechanisms. That is, the double-peaked maxima of solar cycles may be caused by a bi-dynamo mechanism (Du 2015). The second peak of cycle 24 that took place at the year 2014 is stronger than the first peak that took place at year 2012. It can be seen in Figs. 4 and 5 the second peak is dominant due to it consists of a large number of small sunspot groups, both in the northern and southern hemispheres. The first peak contains relatively more number of large sunspot groups.

(Note: Cycle 24 is the smallest solar cycle since cycle 14 (Svalgaard *et al.* 2005; Du and Wang 2011; Javaraiah 2015). As can be seen in Figs. 4 and 5 although the current sunspot cycle 24 is weaker than previous sunspot cycle 23, the number of small sunspot groups at maximum (second peak) of cycle 24 is larger than that at maxima of cycles 21–23, in both the northern and southern hemispheres. Figs. 1 and 2 show that in cycle 24 the peaks of the small sunspot groups are small in both the northern and southern hemispheres and their heights close to the heights of the corresponding peaks of the weak cycle 14. That is, at maximum epoch of cycle 24 there exists a considerable difference between SOON and DPD data. We don't know the reason behind this difference. However, generally at any time small magnetic regions dominate the large ones, and the dominant variations in  $R_Z$  mostly depict the dominant variations in the number of small active regions. Since the cycle 24 is much weaker than cycle 23, one can expect at maximum of cycle 24 the small sunspot groups should not exceed the small sunspot groups at maximum of cycle 23. Therefore, at maximum of cycle 24 the aforesaid behavior of SOON data may be correct. In DPD data NOAA sunspot group number is assigned if it exists and it has not been revised. If no NOAA number was assigned for the group, a NOAA number was given with an additional letter (e.g. "m", "n", etc.). From our way of classification of sunspot groups on the basis of their maximum areas, we found that in the years 2014 and 2015 we have got the large number of small sunspot groups due to the presence of a large number of the daily data records of these years with a NOAA number having the additional letters.)

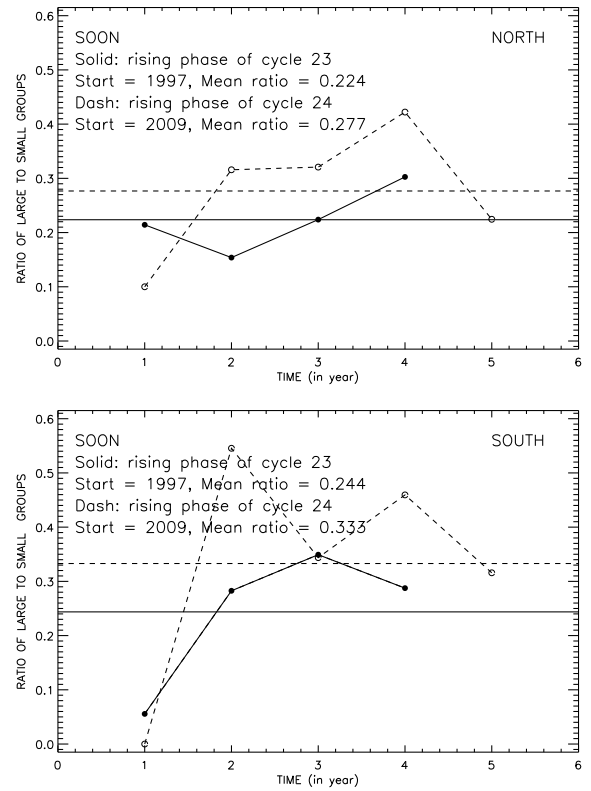
Fig. 7 shows variations in the ratio of the number of large sunspot groups to the number of small sunspot



**Fig. 7** Plots of the values of the ratios of the number of the large sunspot groups to the number of the small sunspot groups in the whole disk during the rising phases of solar cycles 23 and 24 versus time (in the intervals of 27-day), determined from DPD (upper panel) and SOON (lower panel) sunspot group data. (Note: the large and very-large sunspot groups have been combined.) The horizontal lines represent the corresponding mean values. The dotted-dashed and dotted curves represent the variations in the 13-month smoothed monthly  $R_Z$  during the rising phases of cycles 23 and 24, respectively.



**Fig. 8** Plots of the yearly values of the ratios of the numbers of the large sunspot groups to the number of the small sunspot groups determined from the northern hemisphere (upper panel) data and the southern hemisphere (lower panel) data during the rising phases of the cycles' 23 and 24 versus time (year). (Note: the large and very-large sunspot groups have been combined.) The horizontal lines represent the corresponding mean values.



**Fig. 9** The same as Fig. 8 but determined from SOON sunspot group data.

groups in 27-day consecutive intervals during the rising phases of solar cycles 23 and 24. Gopalsawmy *et al.* (2015a) and Gopalswamy *et al.* (2015b) studied the CME variations in 27-day intervals. In order to check whether the large to small sunspot group ratio match with that of CME variation shown in Fig. 7 of Gopalsawmy *et al.* (2015a) here we have also used 27-day intervals. Here we have also combined the large and very-large sunspot groups in order to have a better statistics (Note: the pattern of this combination is highly similar to that of the number of large sunspot groups.) It is found that there are some differences and some similarities within the patterns of the CME and the ratio of the sunspot groups. Figs. 8 and 9 show the variations in the ratio of the number of large to the number of small sunspot groups in the northern and southern hemispheres. In this case for the sake of better statistics we have used yearly data. As can be seen in these figures there are considerable differences in the corresponding variations determined from the SOON and DPD data sets. (The sunspot data from different observatories yield the results which are generally differ with 5%-10% percent). As can be seen in Fig 7, the results determined from both the SOON and DPD data suggest that during the rising phase of cycle 24 in many places the values of the ratios of the number of large to the number of small sunspot groups are larger than the corresponding values during the rising phase of cycle 23. Hence, the average values of the ratios in the rising phase of cycle 24 is considerably larger than the corresponding average values during the rising phase of cycle 23. A similar property can also be seen in Figs. 8 and 9. The difference between the mean values of the ratios of cycles 23 and 24 seem to be slightly larger in the southern hemisphere than in the northern hemisphere.

#### 4 Conclusion and discussion

From the analysis and the results above we can draw the following conclusions:

1. The solar cycle pair (22, 23) violated the G-O rule of sunspot cycles mainly due to, besides in cycle 23 a large deficiency of small sunspot groups in both the northern and southern hemispheres, during cycle 22 a large abundance of small sunspot groups in the southern hemisphere.
2. In the case of large and small sunspot groups the cycle pair (22, 23) violated the G-O rule in the northern and the hemispheres, respectively, suggesting the north-south asymmetry in solar activity has a significant contribution in the violation of G-O rule.

3. In both the northern and southern hemispheres the average ratio of the number of large to the number of small sunspot groups is larger in the rising phase of cycle 24 than that in the same phase of cycle 23. This could be a reason behind the CMEs (halo) are more abundant (in spite of the low sunspot activity) in the rising phase of cycle 24 than in the same phase of cycle 23.

The mechanisms of the generations of the magnetic structures of the large and the small sunspot groups may be associated with plasma dynamics at deeper and shallower layers, respectively, of the Sun's convection zone (Javaraiah and Gokhale 1997b; Javaraiah 2013, and references therein). That is, the magnetic structures of large sunspot groups are deep rooted than the those of small sunspot groups. This could be responsible for the above said difference in the north-south asymmetry of the numbers of large sunspot groups with that of small sunspot groups. The conclusion 3 above is consistent with the known result that the CME productivity increases with active region size (Canfield *et al.* 1999; Ramesh 2010). That is, a large sunspot group could produce relatively a large number of CMEs. Large sunspot groups also live long and their rate of evolution/decay also seem to be relatively large (Javaraiah 2011, 2012b). Hence, during the evolution/decay of a large sunspot group the release of relatively large amount of underneath stored thermal energy may be responsible for more CMEs.

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